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THE APPALACHIAN FOLDS OF CENTRAL PENNSYLVANIA

ROLLIN T. CHAMBERLIN

The observational basis of this study of the Appalachian folding in central Pennsylvania was laid during a special trip on foot from Tyrone to Harrisburg during the summer of 1905. The chief purpose was to measure the dip-angles of the strata at as many stations as possible, that they might be subsequently plotted to scale as a groundwork for restoring the folded structure. Nearly 400 dips were measured, but on plotting them and attempting to restore the structure it was found that they only scantily covered several portions of the section where critical data were especially desirable. This proved to be particularly true of the neighborhood of Harrisburg, where the anticlinal arches are overturned and the shales and slates are so crumpled that, with the time available, it was not possible to trace out many of the minor, but none the less important, complications of structure. As a result it was felt that the material at hand was scarcely adequate for a serious study, and in the hope that a later opportunity might arise to make a further search for the desired data, the work was laid aside. But up to the present no opportunity to again visit this region has presented itself and it has seemed, on reflection, best to proceed with the original purpose, since this was not so much to gain a truer view of this particular case of folding, as to put to working trial certain recent suggestions as to the deductions that may be drawn from data of this sort. In Chamberlin and Salisbury's *Geology*, Vol. II, pp. 125–126, a method is given for deducing the thickness of the shell involved in folding. The present study is a preliminary attempt to make a special application of this method and to see what collateral suggestions might spring from it in practice. For this purpose it is not so material, though it is desirable, that the actual data be complete. In the very nature of the case, most studies of this class must, for the present, deal with incomplete data, since each case has certain indeterminable factors. The necessary deficiencies, however, only make the more serviceable any deductions that can be drawn from such data as are available, if they can be so handled as to extend their significance. It has seemed possible therefore that a discussion based on data that have even serious shortcomings may have some value. It is only because it is hoped that this might prove true that it has been decided to carry out these studies on the present observational data.

The tract of the Appalachian Mountains most readily accessible for dip studies is that which lies along the main line of the Pennsylvania Railroad between Tyrone, in Blair County, and Harrisburg. From Tyrone to Mount Union the railroad, following the Juniata River, crosses the folds in a fairly straight line at right angles to their strike and affords a very good section. But just beyond Mount Union the Juniata turns sharply to the northeast and runs for twenty-five miles parallel to the strike, as far as Lewistown. This offset necessitates a division of the whole cross-section into two parts. From Lewistown to Harrisburg the folds are crossed generally at right angles to the strike with the exception of a few minor curves. This constitutes the second portion. Inasmuch as the second portion commences near Lewistown at the point corresponding to that where the first section left off near Mount Union, it would seem that no great structural error is introduced by ignoring the shift and uniting the two separate parts into one section.

At every available rock-outcrop along each of these lines, the dip of the strata was read with a clinometer compass, using the telegraph poles which are set thirty-eight to the mile as a means of locating the stations. For rapid work of this sort the spacing of the telegraph poles may be used so as to give quite closely the distance intervening between the locations of outcrops. Allowance, of course, must be made whenever the railway-line crosses the folded structure obliquely and curvingly, instead of normal to the strike. Wherever there occurred sudden changes in the angle of dip, or small local folds, diagrammatic sketches were made of the rock-face, and on these sketches the clinometer readings were recorded at the appropriate points. Where there were good outcrops the details of the folded structure were readily discerned, but unfortunately there were frequently considerable areas over which suitable rock-exposures were wanting. In all, nearly four hundred dip-angles were recorded between the nearly horizontally bedded uplands west of Tyrone and the outskirts of Harrisburg.

In plotting the dip-angles to scale on co-ordinate paper, it was found most convenient to represent the distance between two telegraph poles, or one thirty-eighth of a mile, by two millimeters, which was the smallest unit available on the style of paper used. Therefore each mile in nature is represented by seventy-six millimeters on paper. From these plotted dip-angles and the available information upon the location of the contacts of the different formations and their varying thickness, partly obtained in the field and partly from the reports of the Pennsylvania State Survey, the writer has attempted to restore the complete folded section as it is supposed to have been before the ridges were truncated by erosion. Necessarily the uncertainties in the projection of folds are so considerable that this can be regarded only as a rough approximation to the original conditions following the period of folding. It is on the basis of this restored section that the present study has been made.[1]

THE SHORTENING OF THE CRUST

Several estimates of the amount of crustal shortening involved in the folding of these mountains have already been made. Lesley placed the lateral movement of the Appalachian thrusting at forty miles.[2] Claypole[3] divided the folded tract into two parts; the first from the approximately horizontal formations on the northwest, across the eleven principal ranges of mountains to Blue Mountain on the southeast, a total of forty-nine miles; the second, sixteen miles in length, crosses only the Cumberland Valley. By deducting twenty miles of the first section for the flattish tops of the anticlinal crests and the bottoms of the synclinal troughs, and assuming that the remaining twenty-nine miles of strata possessed an average dip of 40°, he arrived at the conclusion that these forty-nine miles of strata, if flattened out, would measure fifty-eight miles. It is not easy to determine the number of folds occurring in the Cumberland Valley, but on the basis of the thickness of strata included in these plications, Claypole reasoned that there could scarcely be less than eight overthrown anticlinal arches in the sixteen miles considered. Adopting Professor Rogers' lowest angle of dip for the southeast legs (45°) and 60°, his lowest estimate for the northwest limbs, he calculated that ninety-five miles of strata had been compressed into these sixteen miles. Considering both sections together, this would mean that a tract of the earth's surface measuring originally one hundred and fifty-three miles had been compressed into sixty-five miles. As Claypole frankly stated, this estimate took account only of the eleven principal folds and ignored the minor flexures.

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[1] For an alternative profile of the Appalachian flexures, a series of dip-readings was made along the Susquehanna River between Harrisburg and the vicinity of Williamsport. But this proved to be a less representative section, and since, in addition, good outcrops were less numerous, only the Tyrone-Harrisburg section will be treated in this article.

[2] J. P. Lesley, cited by Chamberlin and Salisbury, *Geology*, Vol. II, p. 125.

[3] E. W. Claypole, "Pennsylvania before and after the Elevation of the Appalachian Mountains," *Am. Nat.*, Vol. XIX (1885), pp. 257–68.

The present estimate of crustal shortening is made from a measurement of the strata in the plotted cross-section formed as above stated and made to include as much as possible of the minor contortions of the beds. The data for these sections were obtained at the railroad horizon. From the dip-angles, the locations of the formation-contacts, and the thicknesses assigned to the formations, the whole series of beds up to the top of the Pottsville conglomerate were projected over the entire restored section. But as the youngest of these arched strata had to be projected many thousands of feet above the railroad-level to do this, it is to be noted that the farther up in the stratigraphic series the restoration of structure is carried, the more uncertain does it become. The separate strata, being of different material and offering varying resistance to the thrust, cannot always be supposed to wrinkle alike. Minor flexures and local bits of crumpling may fade out in passing up or down, and new ones appear. Hence for the purpose of measuring the length of strata over this section it seemed advisable to choose the stratigraphic horizon which remained nearest to the railway-level. It is to be recognized, of course, that the maximum amount of crustal shortening was probably suffered by the surface beds and that the folds slowly die out downward, but it is believed that whatever lessening of the flexures there may be in the first few thousand feet would be likely to be more than offset by the probable error in projecting folds to such a distance from the observed dips.

For the division from Tyrone to Mount Union (Figs. 1 and 2) the thin, but strongly resistant Oriskany sandstone was chosen for measurement as likely to give the most reliable results. In the second section the Oriskany was also measured as far as the crest of the anticline just before the prominent fault near Iroquois Station (Fig. 4). At the very crest-point of this anticline the measurement was shifted from the Oriskany to the base of the Catskill since the strata soon take a tremendous dip which carries the Oriskany far below the surface. This shift appears permissible since the fold is approxi-

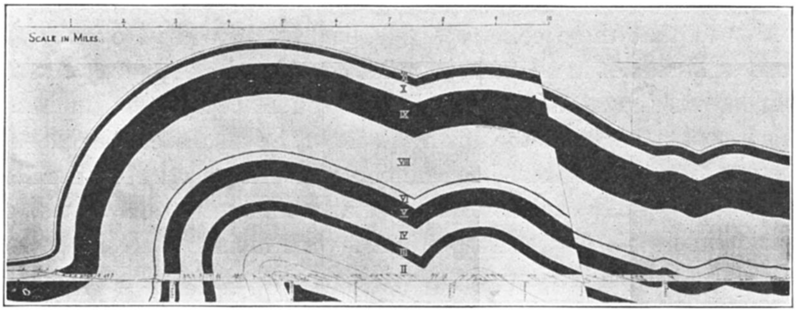

FIG. 1.—A reconstruction of the folded section from the essentially horizontally bedded uplands west of Tyrone nearly to Petersburg. East of Tyrone the dip-angles are plotted on the horizontal line which represents the railroad-level; on the uplands west of Tyrone they are plotted according to the surface topography. The numbers representing the formations are those used by the Pennsylvania Geological Survey: II, Trenton and Calciferous; III, Hudson River shales; IV, Oneida and Medina; V, Clinton; VI, Lower Helderberg; VII, Oriskany; VIII, Chemung; IX, Catskill; X, Pocono; XI, Mauch Chunk; XII, Pottsville conglomerate.

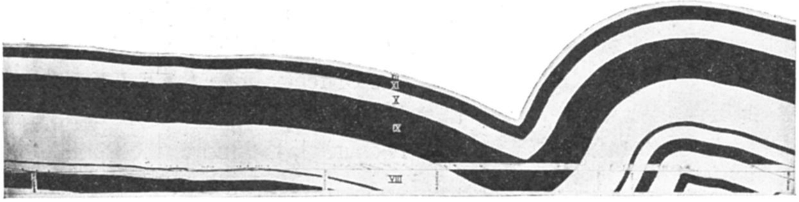

FIG. 2.—Continuation of section from Petersburg to Mount Union

mately symmetrical. The measurement then followed the base of the Catskill to the end of the section (Fig. 5).

To follow and measure the contortions of these two selected formations throughout their length, a copper wire was used. Placed upon the plotted cross-section, this was bent so as to be exactly superimposed upon the line to be measured. This wire, when straightened out and measured, represented very closely the length of the chosen stratum along its tortuous course. As the cross-sections were plotted on millimeter paper all measurements were made in that unit.

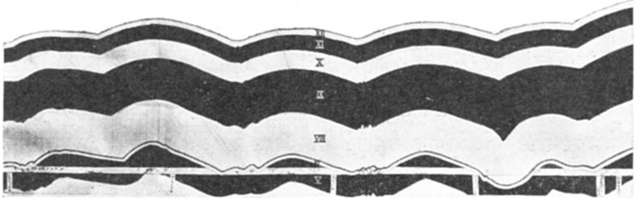

FIG. 3.—Reconstructed section between Lewistown and Durward

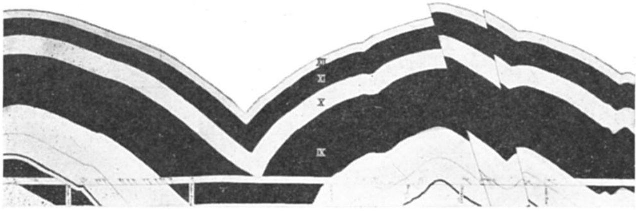

FIG. 4.—Section between Durward and Aqueduct Station

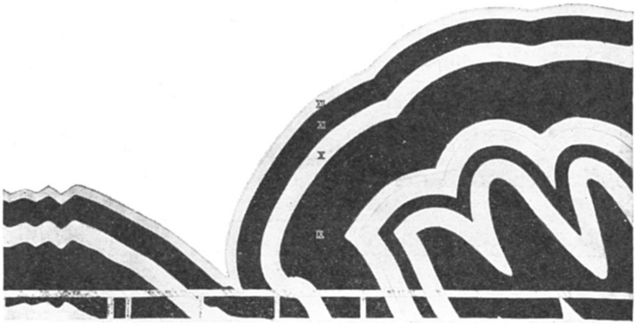

FIG. 5.—Continuation of section from Aqueduct Station to Harrisburg

The total length of the Oriskany stratum as reconstructed in the cross-section from the west end of the folded region to Mount Union (Figs. 1 and 2) was found to measure 2,602 millimeters. The straight-line distance between these points measured on the railroad-level is 2,288 millimeters. The length of the top line of the restored section (the top of the Pottsville) was also measured as a check. It was found to be 2,618 millimeters. If 2,602 millimeters, the length of the Oriskany along the dip, represents the original length of that stratum before the folding took place, and 2,288 millimeters represents the present horizontal length of the section under consideration, there must have been a shortening of this formation to the extent of 314 millimeters, or 12 per cent. of the original length. On the scale used, seventy-six millimeters in the cross-section represents one mile in nature. Converting the figures obtained from a measurement of the plotted section into miles, the length of the Oriskany (2,602 millimeters) becomes 34.2 miles and the horizontal distance, 2,288 millimeters, is equivalent to 30.1 miles. Neglecting other factors, the shortening amounts, therefore, to 4.1 miles.

In the second section the length of the Oriskany from the beginning at Lewistown to the crest-point of the anticline above mentioned between Baileysburg and Iroquois Station was found to measure 1,789 millimeters. At this point the shift was made to the base of the Catskill. The lower limit of this formation, followed to the point where it rises above the railroad-level about half a mile southeast of Marysville, gave a dip distance of 1,070 millimeters. The sum of these two dip measurements gives 2,859 millimeters as the length of these strata between Lewistown and the contact of the Catskill with the Chemung close to the Susquehanna bridge five miles above Harrisburg. On the same scale the present horizontal distance between these points is 2,399 millimeters. This indicates a crustal shortening due to the flexing of the beds, which amounts to 460 millimeters, or 16.1 per cent. of the original length. Translated into miles these figures are respectively 37.6 and 31.5 miles, signifying a shortening of 6.1 miles. The total shortening, therefore, from the beginning of the section west of Tyrone to the point between Marysville and the Susquehanna bridge amounts, on the basis of the assumptions made, to 10.2 miles, 71.8 miles having been compressed to 61.6 miles.

Southeast of the Susquehanna bridge above Harrisburg the data obtained were inadequate and unsatisfactory. The strata to which we must look for guidance here are Hudson River shales and slates, and they are mashed and disturbed to such an extent that often there is danger of mistaking secondary structures for bedding. Wherever observed these beds all dip southeastward at angles varying from 50°–80° in such a way as to indicate overturned folds. But these soft shales furnish the poorest sort of criterion for determining the true character of the folding, because a weak formation of this sort may be much wrinkled, crushed, and appressed, while the stronger strata above may have been merely bowed upward and may not have suffered crumpling to the same extent. In projecting the younger formations over these folded shales, the wrinkles were made to die out slowly. The shale layers were allowed considerable thickening and thinning, but in the stronger layers above little of this distortion was taken into account. It may well be that considerably more thickening of the layers on the crests and troughs, and thinning on the limbs of the folds should be allowed in the upper formations. Since the observed data for this slate and shale belt are so meager and the restoration of the younger formations which once covered this region is so precarious because of this limited knowledge, and because the whole is so much a matter of personal opinion, it has not seemed advisable to state any measurements made upon the reconstructed curves. Some of the layers were measured, however, and upon this basis a rough guess that the original length of these strata was about twice their present horizontal length is ventured. They can scarcely have suffered much less shortening than this, though they may have suffered much more. Claypole believed that these overturned folds resulted from such intense crumpling that into each horizontal mile of present distance there have been squeezed what were originally six miles of flat-lying strata; but this figure seems to me somewhat excessive.

To put these figures together, we have, on the basis of the assumptions made, and subject to other limitations to be mentioned shortly, 71.8 miles reduced to 61.6 miles west of the Susquehanna bridge, and 9.5 miles jammed into the present distance of 4.75 miles between Harrisburg and the Susquehanna bridge, making a total west of Harrisburg of 81 miles compressed into 66 miles.

The various elaborate factors which enter into the problem of crustal movement, and which embarrass quantitative determinations of the shortening, have been ably discussed by Van Hise.[1] These embarrassing factors include the following: (1) The thickening and thinning of the strata in the different parts of the sharper folds. The thickening and thinning are uncertain variables, for which it is difficult to make allowance when only a very limited portion of the whole fold can be observed, as is usually the case. (2) The variation in the closeness of the folding in passing upward or downward from the layer on which the observations were made. The farther upward from the recorded data the folds must be projected, obviously the greater the error likely to creep in. It was for this reason that, in the case in hand, the measurements on the plotted section were made along those strata which departed the least from the railroad horizon. (3) Subsequent relaxation of the strata under the influence of gravity. This may take the form of gliding on the limbs of the folds where a new series of corrugations may be developed; it may also be manifested in the opening of fissures and in the phenomena of normal faulting. The effect of these secondary phenomena involving dilatation of the surface shell subsequent to the folding period is to cause an overestimate of the extent of the crustal shortening. But the quantitative importance of gravity wrinkling in the Appalachian region arising from relaxation and creep since the period of folding is, for the present at least, impossible of determination, but it is probably not seriously large.

It is also probable, on the whole, that in addition to the folding the lateral thrusts have caused a certain amount of mashing and compacting of the material of the beds. A few measurements upon the wax-and-plaster folds developed experimentally by Willis[2] show that the decrease in the length of the layers due to mashing alone, varied from 1 up to 10 per cent. of the original length. The total shortening of all kinds in the illustrations selected for measurement varied from about 15 per cent. to somewhat more than 60 per cent.

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[1] C. R. Van Hise, "Estimates and Causes of Crustal Shortening," *Jour. of Geol.*, Vol. VI (1898), pp. 10–64.

[2] Bailey Willis, "The Mechanics of Appalachian Structure," *Thirteenth Ann. Rept., U.S. Geol. Surv.* (1891–92), Pt. II, pp. 211–82.

The variation in the amount of linear reduction due to mashing appears to correspond to differences in the character of the material used in the experiments. As a rule the softer the material in the layers the greater the degree of mashing; when more plaster and less wax and turpentine stiffened the layers, they were much less compacted. An average figure for the shortening of the layers due to mashing in these experiments by Willis would seem to lie in the neighborhood of 5 per cent. In the case of the Appalachians, however, the amount to be allowed for shortening due to mashing of the strata in addition to that resulting from the corrugation must be left largely to conjecture, but as the rock-formations are relatively much stiffer than the wax-and-plaster layers used in the experiments, it would seem likely that the figure for the mountains should be considerably less than 5 per cent.

Tending to offset the shortening due to the mashing of the rocks is the subsequent elongation of the strata arising from the opening of fissures, jointing, cementation by infiltration, and the penetration of igneous intrusions. Several former fissures near the junction of the Juniata with the Susquehanna have been rendered conspicuous by the intrusion of Mesozoic trappean magmas which have solidified within them. No attempt at any quantitative estimate of their importance in crustal shortening is made here. Whether the importance of these various secondary factors is material and whether, if ignored, the balance of their sum-total tends toward an overestimate, or an underestimate, of the true extent of the crustal shortening, is here left to the individual judgment of each geologist guided by his own experience and insight. The results reached later may have some reflex bearings on these points.

THE HEIGHT OF THE FOLDED TRACT

For a study of the dynamics of crustal warping and the nature and dimension of the mountain-building movements, one of the necessary factors to be determined is the amount of vertical bulging. To determine the extent of the upswelling connected with the folding it is necessary to measure the height of the newly folded ranges above the average height of the same region before the movements began. The first requirement is a base plain to which may be referred the attitude of the land surface before the folding took place; the second requirement is a visible base-line available at the present day, above which the projection of the folded tract is to be measured. In view of the fact that the critical period of folding occurred as far back in geologic history as the close of the Paleozoic, and in view of the still more compromising fact that other diastrophic movements have disturbed the Appalachian belt since that time, it might at first seem that such planes of reference could not reasonably be hoped for. But fortunately the physiographic history of the Appalachians has been admirably arranged to meet the requirements of the case.

The last beds to be deposited in the present mountain tract were the upper strata of the Coal Measures. From the nature of these beds, particularly the persistence of coal repeated in a considerable number of separate seams over adjacent areas of wide extent, it is confidently inferred that the Appalachian region during the Upper Carboniferous must have constituted an almost perfect plain of sedimentation, at times just at, or a few feet above, the sea-level, and at other times but slightly submerged. The very considerable areas over which individual coal-seams may be traced testify to the uniformly level condition of the region. It was this rather remarkable plain of sedimentation, warped and wrinkled by the throes of the dying Paleozoic, that rose into the great Appalachian plications.

On the other hand, the mountains thus formed had their day and were gone before the end of the Mesozoic, when a new plain had been established. The Kittatinny base-level, strikingly visible even today in the level crest-lines of all the major ridges of this portion of Pennsylvania, shows that by the close of the Cretaceous, the former mountain tract had been beveled till the land again stood close to the sea-level.

Thus the Appalachian region started approximately from the sea-level, was thrust up into tremendous folds, and then planed down by erosion again essentially to the level of the sea. If no other diastrophic movements intervened to complicate the case, the total upwarping of the crust should be expressed by the average height of the freshly folded tract above the sea, and if the height of the sea relative to the land of this area remained the same till the Kittatinny base-plain was established, that plain should constitute an absolute base above which the hypothetically restored folded section could be measured. But the sea-level undoubtedly did not remain stationary through such a long period of time. Such a ponderous series of mountain-masses must have been subject to some settling. Possibly a mathematical analysis of the mechanics involved might furnish a theoretical figure for the possible isostatic changes, but the problem is quite beyond the reach of the present paper.

Some rise of ocean-level is also to be expected on account of the filling of the ocean-basin with the material removed from the mountains in the process of peneplanation, and obviously sedimentation in other portions of the oceanic area would be equally effective in changing the water-level; and hence the great ramification of the problem.

Some crustal warping also appears to have occurred at the east during the early Mesozoic. The Newark series of sediments, which were laid down in local depressions in southeastern Pennsylvania during the Triassic, seem to imply a certain amount of downwarping in that region.[1] Later, at the close of the Triassic, or early in the Jurassic, the deposition was stopped by the reversal of the conditions which started it.[2] A moderate elevation with tilting affected the Newark beds. But to what extent these warpings in the eastern part of the state affected the mountain-section under consideration is uncertain, and whether the sum-total of the movements should be regarded as upward or downward must remain, for the present, largely a matter of conjecture.

But in general the period of erosion and base-leveling which was inaugurated by the mountain-building at the close of the Paleozoic and which resulted in the Kittatinny plain was one of comparative quiescence and, on account of its freedom from the more important dynamic movements, the present case is probably as favorable as any other which could be selected.

It will therefore be assumed that when the folding commenced the formations were practically horizontal and the upper surface of the youngest beds essentially at sea-level. It will also be assumed that the Kittatinny base-plain in turn represents somewhat approximately a horizon equivalent to the sea-level from which the strata were upwarped. Estimates of the height of the folded tract may therefore be measured from the Kittatinny plain as a base. In this way the Tertiary uplifts and any other disturbing factors since the Cretaceous are eliminated.

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[1] Chamberlin and Salisbury, *Geology*, Vol. III, pp. 7-9.

[2] W. M. Davis, "The Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, Vol. I (1889), p. 196.

In the reconstructed section no beds younger than the Pottsville conglomerate were included, for the reason that no younger formations now occur in the region studied. It seems highly probable, however, that the Allegheny, Conemaugh, Monongahela, and possibly the Dunkard formations once covered this portion of the Appalachians, and were incorporated in the folds but have since been removed by erosion. These formations vary considerably in thickness in different localities. In Westmoreland County the Lower Productive, Lower Barren, Upper Productive, and Upper Barren Measures have a total thickness of 1,477 feet.[1] Campbell gives 1,540 feet for the Coal Measures above the Pottsville in southwestern Pennsylvania.[2] These are on the southwest side of the area under consideration; in the anthracite regions to the northeast, the Coal Measures appear to be thicker—in the northern field 1,800 feet, in the middle 1,500 feet, while they attain a total aggregate of 2,500 feet in the southern field, and it is not certain that some layers may not have been removed by erosion from each of these districts.[3] The thickness of these formations over the Tyrone-Harrisburg mountain-section was perhaps of about the same order of magnitude, though this must always remain a matter of conjecture. A belt representing the missing Coal Measures therefore belongs above the Pottsville, but was omitted from the cross-sections because of the uncertainty as to the thickness and former extent of these beds. An average figure for the thickness of these missing beds is to be added to the height of the folded section in the following estimates.

But the Kittatinny base-level maintains also somewhat fluctuating elevations above the railroad tracks. Generally about 1,000 or 1,100 feet separate the two horizons, but at points in Huntingdon

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[1] J. J. Stevenson, *Second Geol. Surv. Pennsylvania*, 1876, Fayette and Westmoreland Districts.

[2] M. R. Campbell, *Masonville-Unionville Folio*, U.S. Geol. Surv.

[3] Penn. Geol. Surv., *Summary Final Rept.*, 1895, Vol. III, Part 1, "Carboniferous," p. 1924.

County the peneplain rises to approximately 1,500 feet above the railroad. As the measurements were all made from the railroad, this correction for the height of the Kittatinny base-level above it should be subtracted from the total height of the folds. Here then are two corrections of opposite sorts, one positive and the other negative. While the figure for the positive correction would seem likely to be somewhat in excess of the figure to be subtracted, there is no good basis for close figuring, and the safest thing, on the whole, seems to be to allow the present height of the peneplain above the railroad which served as a base-line for collecting the data and constructing the cross-section, to offset what younger strata there may have been above the Pottsville conglomerate. Measuring then from the railroad-level, at which the data were collected, to the top of the Pottsville should give, perhaps, as good an approximation to the height of the original folds as a similar measurement from the Kittatinny peneplain to the more uncertain upper surface of the Upper Barren Measures. These more convenient and readily available measuring-points will therefore be taken.

If, however, one should prefer to strike a general average for the thickness of these measures over the various neighboring areas where they now occur, and to assume that this full thickness of strata covered the whole extent of the Tyrone-Harrisburg section, he may readily do so. From the data given by Stevenson,[1] a figure of 1,700–1,800 feet would seem a fair one to adopt. If 1,100 feet represents the average difference in altitude between the Pennsylvania Railroad and the Kittatinny base-level, there remain, following this assumption, 600–700 feet to be added to the estimate of the height of the folded tract to be made shortly. But it is not at all certain that this full thickness of post-Pottsville sediments once extended completely over this area, and, in addition, it would seem that the thicknesses of the various Paleozoics in the reconstructed sections are more likely to be overestimates than underestimates. Because of a suspicion that possibly somewhat excessive thicknesses may have been allowed for some of the restored formations in the section, the writer prefers not to add this last correction to the total height of the folded belt.

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[1] J. J. Stevenson, "Carboniferous of the Appalachian Basin," *Bull. Geol. Soc. Amer.*, Vol. XVII, pp. 65–228, and Vol. XVIII, pp. 29–178.

To determine their average vertical dimension, the cross-sections were photographed and the glazed-paper prints carefully cut at the railroad-level as base-line, and the top of the Pottsville conglomerate as the sky-line, and the resulting paper equivalents of the sections then weighed on delicate balances. At the same time similar strips of duplicate prints, cut to represent a uniform height of one mile of strata above the base-line, were also weighed. Thus weighed in the five separate sections, the results were:

	Grams
Section 1 weighed	0.4819
Scale representing same area weighed, per mile of height	0.1394
Hence average height of reconstructed beds of Section 1 is 0.4819/0.1394=3.45 miles.	
Section 2 weighed	0.4346
Scale representing strata uniformly 1 mile thick for this distance weighed	0.1833
Hence average height of reconstructed beds of Section 2 is 0.4346/0.1833=2.37 miles.	
Section 3 weighed	0.4231
Scale representing 1 mile of strata over this area weighed	0.1466
Hence average height of reconstructed beds of Section 3 is 0.4231/0.1466=2.88 miles.	
Section 4 weighed	0.3981
Scale for this distance weighed	0.1466
Hence average height of reconstructed beds of Section 4 is 0.3981/0.1466=2.71 miles.	
Section 5 weighed	0.5402
Scale for this distance weighed	0.1466
Hence average height of reconstructed beds of Section 5 is 0.5402/0.1466=3.68 miles.	

The general average height of the strata over the last four sections can be obtained directly by dividing the sum of the weights of the four paper sections by the total weight per mile of elevation of the corresponding scales.

	Grams
Total weight of Sections 2, 3, 4, and 5	1.7960
Total weight of corresponding unit mile scales	0.6231
Average height for these sections, 2.88 miles.	

Section 1 cannot be averaged in thus, as it was photographed on a slightly different scale. But the length of Section 1 on the original plat is 1,139 millimeters, while the total length of the other four sections is 3,910 millimeters.

Therefore $\frac{(3.45\times1139)+(2.88\times3910)}{1139+3910}=3.01$ miles, the average height of the top of the restored Pottsville conglomerate over the area from Tyrone to Harrisburg.

This figure of 3 miles applies to the whole distance plotted. For the purpose of study it was also desirable to know the average height of the folded tract for the section from Tyrone only to the Catskill-Chemung contact just southeast of Marysville. The photo print of Section 5 was therefore carefully cut at this point and the northwestern portion placed on the balance. This portion weighed 0.2100 grams, while Section 5 originally weighed 0.5402 grams. This northwestern portion of Section 5 measured 559 millimeters on the large plot compared with 921 millimeters linear measurement for the whole of Section 5. Calculated on this basis the average original height of the Pottsville conglomerate from Tyrone to Marysville comes out 2.80 miles.

THICKNESS OF THE FOLDED SHELL

If one knows the average height to which the freshly folded tract was elevated, together with the amount of lateral shortening which has caused this elevation, it is a simple matter to calculate the thickness of the shell which suffered folding, neglecting compression, etc. By using the figures just obtained—81 miles compressed into 66 miles with a resulting mean elevation of 3 miles—one might make an estimate of the average thickness of corrugated strata across the whole tract. But as the thickness of the wrinkled shell is liable to be variable, it is necessary, in order to ascertain the true significance of the thickness and its variability, to consider separately the several dissimilar parts which make up the section. The most elevated tracts were on the flanks of the mountain-belt, at the two ends of the section under consideration. In both of these the Trenton limestone comes to the surface at the present time. Between these two greatest upthrusts is a long tract of lesser elevation and less acute folding. To bring out the significance of these variations, the six sections into which the whole cross-section was cut will each be considered separately.

Section 1, comprising the great anticlinal east of Tyrone, was shortened from 17.8 miles to 14.9 miles, while the top of the Pottsville conglomerate was raised to a mean height of 3.45 miles. To produce this relation between shortening and elevation, a thickness of crust amounting to 17.7 miles must have been compressed, provided there were no increase in the density of the rocks.[1]

Section 2 was found to have been shortened from 16.3 miles to 15.2 miles. As this block was raised 2.37 miles on the average by this folding, it must have had an original thickness of approximately 32.7 miles, on the assumption, of course, that the same degree of shortening persisted throughout the whole block.

Section 3 appears to have been reduced horizontally from 13.56 miles to 12.1 miles, and to have been elevated 2.88 miles. The same method of computation would assign to this block a thickness of 23.8 miles.

Section 4, which is now 12.1 miles in length, seems to have covered originally 14.44 miles. Having been upthrust to the extent of 2.71 miles, it should have a depth of 14.0 miles.

Section 5*a*, shortened from 9.6 into 7.37 miles and upthrust 2.36 miles, should constitute a block extending 7.8 miles below the measuring base.

Section 5*b*, the Cumberland County upswelling between the Susquehanna bridge and Harrisburg, rose to the extent of about 5.75 miles. I have assumed a shortening of two into one, or 9.5 miles reduced to 4.75 miles of horizontal distance. On this basis the thickness of the crust required would be only 5.75 miles, assuming uniform shortening throughout this thickness. If a greater amount of lateral compression be taken, the thickness of shell required becomes correspondingly diminished. Claypole, it will be remembered, assumed a shortening from 6 to 1 for the whole of the Cumberland Valley. On this assumption, provided the height of the folds remained the same, only about one mile of strata would need to be compressed to give the results.

[1] This method of dealing with the folded block takes no account, either of the possible increase in the density of the crumpled rocks, or of the possibility that there may have been some relief from the strains by down-folding as well as up-folding. But any changes in density must be slight, and any considerable down-folding against the great resistance of the underlying rocks seems improbable.

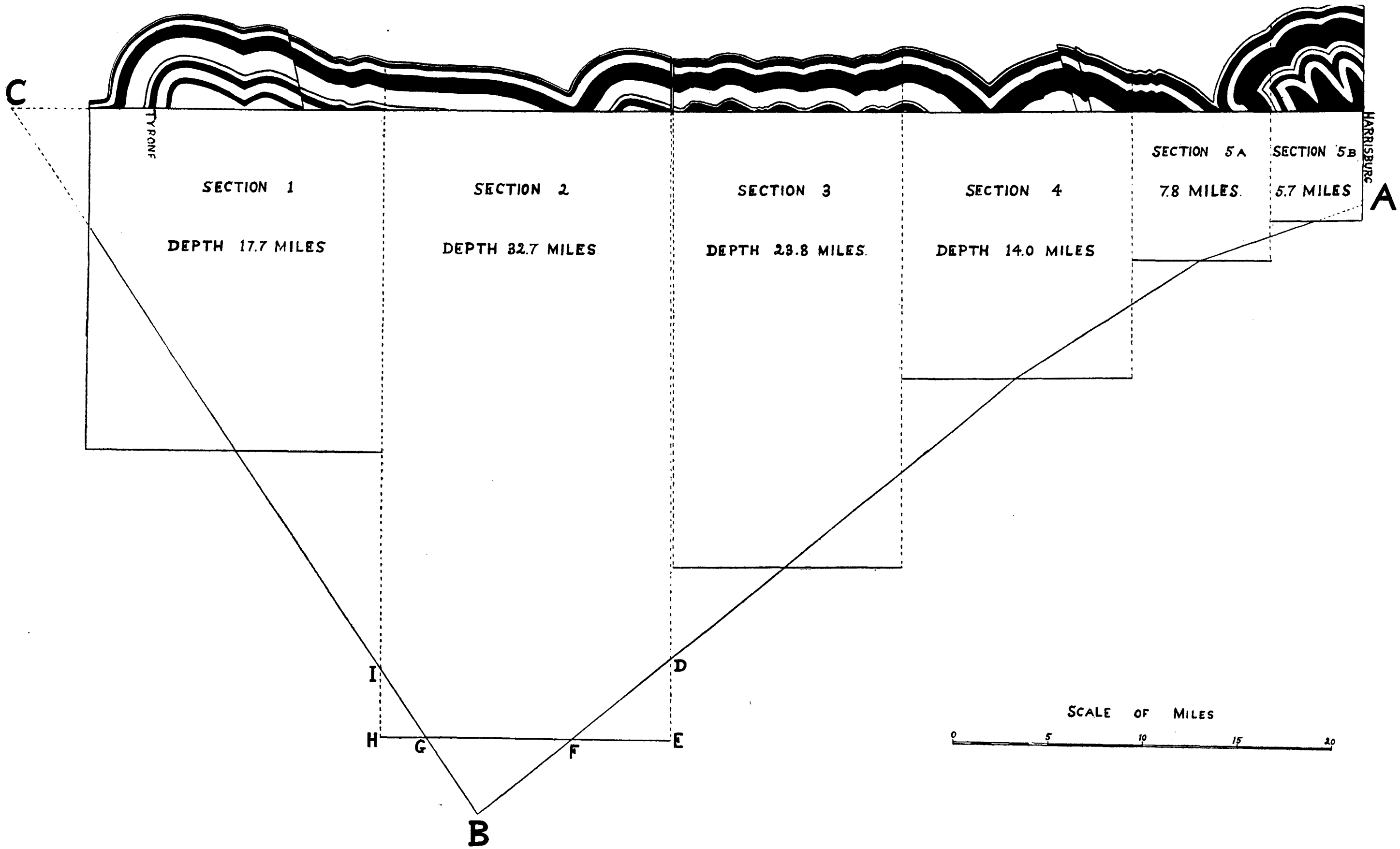

FIG. 6.—Plot of the Tyrone-Harrisburg folded section representing the thickness of deformed shell beneath each of the six blocks as developed by the above methods of measurement. The lines *AB* and *BC* are drawn through the middle points of the bottom lines of each of these blocks, except Section 2, the apex block. The triangle *GBF* is drawn equal in area to the sum of the triangles *GHI* and *DEF*. The whole deformed mass appears, subject to the necessary limitations, to be the triangular block *ABC*.

NATURE OF THE DEFORMED BLOCK

Fig. 6 expresses diagrammatically the variable thickness of the shell beneath the different sections of the folded tract, as developed by this method of analysis. The separate sections are each drawn to true scale as independent blocks, and constitute a series of steps. As the diagram rather strikingly shows, the folded shell is thinnest at the eastern end of the section and thence thickens step by step westward up to a certain turning-point, beyond which it shallows even more quickly. The regularity of these descending steps, when first worked out, came as a distinct surprise as it was not anticipated from the simple inspection of the reconstructed cross-section. It seems to be a feature of much significance and appears to give a concrete picture of how the deformation occurred.

In order to approximate more closely what may be supposed to have been the actual nature of the deformation, the broken lines *AB* and *BC* are drawn as substitutes for the artificial steps. These pass through the middle points of the bottom lines of each block with the exception of Section 2, the deepest segment, and hence the resulting sectional area of each segment remains essentially as it was in the rectangular block. Segment 2 is the apex, and to keep its area the same as the original block, the triangle *FBG* is constructed so as to equal in area the sum of the triangles *DEF* and *GHI*. At the same time Segments 1 and 3 retain their original areas.

Taken together the stepping-blocks from which the lines *AB* and *BC* have been derived are very suggestive. The thrust which produced these great mountain-flexures came presumably from the direction of the Atlantic Ocean. The near-by eastern side of the folded tract suffered more intense crumpling than the more remote western portion, the sharpest folding lying in the tract east of the present Blue Ridge. West of this the surface folds slowly die out with, however, one great fold at the west end. Simultaneously with the diminishing intensity of the folds, the thickness of the folded shell increases. Apparently the thrust from the Atlantic Ocean affected at first a moderately thin crust of five or six miles, or perhaps even less, which it squeezed intensely. From this thin, intensely compressed strip the lateral thrust was transmitted to the region lying immediately west; but instead of being communicated simply to the upper five or six miles of strata, the strains appear to have diverged into an increasingly thick shell. In other words, the shear plane plunged downward. After reaching the maximum depth beneath Section 2, the limit of the deformed mass was deflected rapidly toward the surface. The deformed block thus assumed, in a general way, the form of a triangular prism.

That the analysis of field data should develop a deformed block of this shape and attitude was wholly unexpected but behavior of this sort is, in reality, entirely in accord with what the principles of mechanics imply for such bodies under lateral stress. In solid bodies under direct pressure, fracturing and shearing usually take place along the planes of greatest tangential stress. Becker has developed the application of this principle mathematically in the case of strained rocks. "A direct, uniformly distributed pressure of sufficient intensity, applied to an elastic brittle mass presenting great resistance to deformation, would induce fracture. The ruptures would take place along those lines subject to the greatest tangential strain, since these are the directions in which material would first be strained beyond endurance. These lines would stand at 45° to the line of force if the mass presented infinite resistance to deformation."[1] Hoskins in his analysis of strain and stress applied to the flow and fracture of rocks has also discussed this principle: "Simple sliding at any instance takes place along two sets of planes at right angles to each other and inclined 45° to the directions of elongation and shortening at that instant."[2] Leith's doctrine of fracture-cleavage is dependent upon the same principle and he agrees with Becker on the fundamental principle involved: "If fractures occur in irrotational strains, these follow intersecting planes approximately 45° to the greatest pressure—planes of greatest tangential stress."[3] The exact angle, however, varies somewhat with the nature of the substance and with the stress-conditions. In the Appalachians the greatest mountain-building pressure acted essentially horizontally. The planes of greatest tangential stress should, therefore, dip at angles somewhere in the neighborhood of 45°, and may plunge downward or upward. Whatever fracturing or shearing there be, resulting from these lateral mountain-building thrusts, should follow these dipping-planes as lines of least resistance. If the mass under stress be prevented from undergoing relative motion in these directions, a much greater force would be necessary to compel it to move in any other direction.[1]

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[1] G. F. Becker, "Finite Homogeneous Strain, Flow and Rupture of Rocks," *Bull. Geol. Soc. Amer.*, Vol. IV (1893), p. 50.

[2] L. M. Hoskins, "Flow and Fracture of Rocks as Related to Structure," *Sixteenth Ann. Rept. U.S. Geol. Surv.* (1894–95), Pt. I, p. 865.

[3] C. K. Leith, "Rock Cleavage," *Bull. 239, U.S. Geol. Surv.* (1905), p. 121.

Perfectly in accord with these deductions and bearing directly upon the case under analysis, is the experimental work of Daubrée

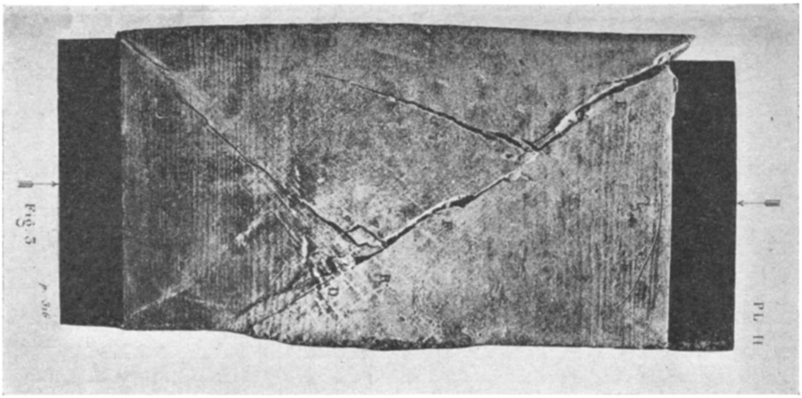

FIG. 7.—An experiment by Daubrée. The material of this prism was a carefully prepared mixture of plaster, wax, and resin, molded so as to be as nearly homogeneous as possible. When subjected to direct pressure at both ends, a wedge-shaped mass was fractured loose and lifted slightly out of its bed. Several systems of fractures have developed.

upon the problem of jointing. This brilliant experimenter subjected blocks of wax to direct pressure operating on the two opposite sides of the block. There were developed in this way two systems of fractures which were inclined to the direction of pressure at angles approximating 45°, and which, at the same time, bear a most striking resemblance to the Appalachian Mountain block *ABC* developed in Fig. 6. Fig. 7 is copied directly from one of Daubrée's plates.[2] The two figures form an instructive comparison; the one, developed from an analysis of data collected in the field without forecast of the result; the other, a photographic record of a direct experiment. In

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[1] G. F. Becker, *op. cit.*, p. 47.

[2] A. Daubrée, *Etudes synthétiques de géologie expérimentale*, T. I, p. 316, Plate II, Fig. 3.

Daubrée's experiment a triangular prismatic mass has been fractured from the main block, and somewhat lifted. That it did not fold was no doubt due to the absence of adequate gravitative pressure. In the case of the earth-block the gravitative pressures at less than the block-depths exceeded the folding-strength of the strata and the wedge-shaped block deformed instead of simply rising *en masse.*

Both theoretical considerations and Daubrée's experiments show that angles of fracturing and shearing vary through a rather wide range, especially as the character of the material varies, and the correspondence of the Appalachian block to theory is perhaps closer than might be expected. In Fig. 6 the line *AB* in its deeper portion dips northwest at about 40°, while *BC*, as it is drawn, dips 54° southeast. In theory the fracture-dips in the upper horizons should normally be lower than 45° while the shear-dip in the lower, less brittle horizons, should be higher than 45°, and this seems to be exemplified in Fig. 6 and would no doubt be more strongly shown if the deformation had gone farther.

As previously stated, the greatest folds in this Pennsylvanian section lie at the two ends. The computed section in depth shows that these end portions are the thinnest and hence most susceptible to folding. The central portion descends far below the fracture-zone—and perhaps below the zone of typical folding—into the zone of quasi-flowage or plastic deformation, and this no doubt modifies the surface-deformation of this part.

At the western end the Tyrone fold seems to have been on the eve of passing into a fault when the movement ceased. Farther south faults of considerable throw have actually occurred in like positions at the inland border of the folded tract. In some parts of Tennessee the deformed belt is abruptly terminated on its western side by a sharp thrust-fault beyond which rest undisturbed horizontal beds.[1] The shell seems here to have been broken by a thrust analogous to that along *BC* in Fig. 6, and the deformed block thrust outward along the shearing-plane. The undisturbed strata lying just west of the fault indicate that the portion of the shell just outside of the disturbed block, on the west side, has not participated in the deformation. The deep plunge of the shear-plane near the western limit of the

[1] Briceville, *Tenn. Folio,* U.S. Geol. Surv

folded belt suggests that this deep insetting may constitute the mode by which the moving shell anchors itself in the less moving mass below and thus determines where the movement shall cease and the folding shall take place. This function I think is usually assigned to some specially stable portion of the earth-body. The plunge is here correlated with thick sedimentation and this may be an agency in inducing the plunge. If other cases shall support this suggestion it may offer a new view of the well-known relation between thick sedimentation and mountain-folding.

In Fig. 6 the line *BC* does not pass through the point where the strata were being shaped preparatory to faulting. This may be due to inaccuracies in the field work and in the reconstructed section. But Daubrée's experiment showed that there may be fracturing along several closely parallel lines near the edge of the moved block and that these may be broadly included in the accommodation zone. The angle *ABC* at the apex of the block is not far from a right angle. The fact that it is slightly less than 90° may be due perhaps to the fact that the triangular block has been laterally compressed, which would lessen the original angle at the apex, but such an explanation is not required as the variations of the angle natural to the case more than cover the departure from a right angle.

The likelihood of a zone of accommodation between the folded shell and the less movable interior where deformation by flowage is presumed to be the prevalent type, has been brought out in Chamberlin and Salisbury's *Geology*.[1] Near Harrisburg the moderately thin movable shell seems to have been so sharply crumpled that the adjustment between it and the solid support beneath would seem to have been accompanied by much shearing. But west of the Blue Ridge, where the folding was less intense and the compression was distributed through a much thicker segment, the adjustment between the more movable portion above and the less movable portion below may have been accomplished mainly by distributive shear. The flexures on the surface presumably pass downward into the zone of quasi-flowage where they accommodated themselves by distributive deformation.

Turning back from these details to the general problem of estimating the thickness of the folded shell, it may be recalled that the calculation commences with three dimensions obtained from the field studies, viz.: (1) the present horizontal distance across the folded section, (2) the original length of the same block before folding, and (3) the estimated average height to which the folded beds were thrust. Obviously the nature of the result obtained by this method of inspection is dependent upon the relation between the amount of crustal shortening and the height to which the beds have been raised in consequence of this shortening. Clearly, the greater the horizontal shortening of the folded block in proportion to the resulting vertical bulge, the thinner that block must be; and likewise, the less the horizontal shortening in proportion to the average height of upwarped beds, the thicker the deformed shell must be. In the Pennsylvania section considered, the less closely folded strata between the Blue Ridge and the western anticlinorium stood considerably higher in proportion to the amount of lateral shortening suffered than did the intensely folded beds to the east. Because of this, the calculations indicate a deformed shell increasing in depth to the maximum point beneath the slightly deformed region in Section 2 and thinning again beneath the anticline at the west end. These calculations, of course, assume that the folds have derived their height solely from the upthrusts of the crumpling process, and that the height of each particular area has been determined by the extent of the plication directly beneath it. If these assumptions are at variance with the facts, the conclusions are correspondingly at fault. The results, however, seem to imply that the assumptions are not seriously at fault.

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[1] Vol. II, p. 130.

For the sake of simplicity, it has been assumed that in these shortened blocks the amount of shortening deduced from the present surface beds has continued undiminished throughout the whole thickness of each block. But such uniformity is not to be expected since the thrusts of the upper and lower parts of the shell are probably not always the same and one mode of deformation doubtless grades into another. This complicating factor must lessen somewhat the significance of the numerical figures obtained, without however detracting seriously from the general nature of the results.

So far as a single test may go in justifying a method of inquiry, this trial of the suggested mode of determining the thickness of the shell involved in mountain-folding may be regarded as not only sustaining the value of the method, but as indicating forms of application whose values were not anticipated.